New Dynamic Muscle Fatigue Model to Limit Musculo-Skeletal Disorder

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ABSTRACT

Muscle fatigue is one of the reason leads to Musculo-Skeletal Disorder(MSD). Automation in today's industries makes human effort very less, but still there are many industries in which human have to do complex and repetitive tasks manually. The society/companies have to pay attention on this issue due to the new laws on penibility or repetitive tasks. The objective of this paper is to experimentally validate a new dynamic muscle fatigue model using electromyography (EMG) and Maximum voluntary contraction (MVC). A new model is developed by introducing a co-contraction factor '*n*' in the Ruina Ma's dynamic muscle fatigue model. The experimental data of ten subjects are used to analyze the muscle activities and muscle fatigue during extension-flexion motion of the arm on a constant absolute value of the external load. The findings for co-contraction factor shows that the fatigue increases when co-contraction area decreases. The dynamic muscle fatigue model is validated using the MVC data, fatigue rate and co-contraction factor of the subjects.

Keywords

Muscle fatigue, maximum voluntary contraction (MVC), muscle fatigue model, co-contraction, fatigue rate, electromyography (EMG)

1. INTRODUCTION

In the field of industrial bio-mechanics, the fatigue is defined as "any reduction in the maximal capacity to generate the force and power output". In industries, mostly repetitive manual tasks tends to work related MSD problems [15, 17]. Some times people have to work more on the same repetitive task which can be painful [5, 6] and leads to MSD [1, 16] due to muscle fatigue [15]. To avoid MSD, the study of muscle fatigue is very important. Various static and dynamic muscle fatigue models are proposed earlier to study muscle fatigue [2, 4, 9, 18, 19, 20]. Liang's fatigue model [9] have experiment validation for fatigue and effect of recovery in arm with static drilling posture. Silva [13] simulate the hill model and validate it using opensim. Some Dynamic fatigue models are also introduced [3, 7, 11]. A Dynamic Muscle Fatigue Model [12] has been proposed to describe the fatigue process of muscle groups. However, no consideration about the co-contraction of paired muscles is taken. Missenard [14] explains the effect of fatigue and co-contraction on the accuracy of arms motion. However, no consideration about the co-contraction of paired muscles is taken. The main objective of this study is to revise this dynamic muscle fatigue model by including the factor of co-contraction of paired muscles, as well as to validate it through mathematics and experiments. For now in this article, we mainly focus on the study of muscle co-contraction activity, using elbow joint's muscle groups as target. With the assistance of EMG, the function of co-contraction is confirmed and calculated.

*(This work is supported by Erasmus Mundus HERITAGE Project funded by the European Commission and coordinated by Ecole Centrale de Nantes, France).

VRIC 16, March 23–25, 2016, Laval, France

– X-XXXXX-XX-X/XX/XX.
DOI: 10.1145/1235

2. PROPOSED DYNAMIC MODEL OF MUSCULAR FATIGUE

The dynamic muscle fatigue model is applicable on the dynamic motion of the human body parts.A dynamic muscle fatigue model is proposed by Liang Ma [9] [8] firstly applied on static drilling task. Ruina Ma [11][12] develops this model for the dynamic motions like push/pull operation of the arm. However, the co-contraction of the muscles are not included in both the models. In dynamic muscle fatigue model [10], we select two parameters Γ_{joint} and Γ_{MVC} to build our muscle fatigue model. The hypotheses can then be incorporated into a mathematical model of muscle fatigue which is expressed as follows:

$$\frac{d\Gamma_{cem}(t)}{dt} = -k.n.\frac{\Gamma_{cem}}{\Gamma_{MVC}}\Gamma_{joint}(t) \tag{1}$$

where, k is the fatigue factor and n is the co-contraction factor.

And, if Γ_{Joint} and Γ_{MVC} held constant, the model can then simplify as follows:

$$\Gamma_{cem}(t) = \Gamma_{MVC}.\mathrm{e}^{-k.n.Ct}, \quad \{\text{where,} \quad C = \frac{\Gamma_{Joint}}{\Gamma_{MVC}}\} \tag{2}$$

$$k = \frac{-1}{n.Ct}.\ln\left(\frac{\Gamma_{cem}(t)}{\Gamma_{MVC}}\right) \tag{3}$$

The other parameters for this model are same as in table 1. n is co-contraction factor.

Elements	Unit	Description
k	min^{-1}	Fatigue factor, constant
Γ_{MVC}	N.m	Maximum torque on joint
Γ_{Joint}	N.m	Torque from external load
Γ_{cem}	N.m	Current capacity of the muscle

Table 1: Parameters of dynamic muscle fatigue model

2.1 Co-contraction factor 'n'

The co-contraction is the simultaneous contraction of both the agonist and antagonist muscle around a joint to hold a stable position at a time. Assumptions made for finding co-contraction factor are as follows:

1. The co-contraction is the common intersecting area between the two group of acting muscles.
2. The co-contraction factor will be the same for each agonist and antagonist activities.

The co-contraction area can be understand by the figure 1. This figure is just an example representation of a motion cycle. In this figure, we can see the common EMG activity between bicep and tricep muscle shown by the orange color, which is co-contraction area C_A. The formula for calculating the co-contraction area from EMG activities is given in equation 4. The trapezius activity shown along with the two muscles is co-activation.

$$C_A = \frac{\int_{t_0}^{t_{100}} EMG_{min} \times dt}{\int_{t_0}^{t_{100}} [EMG_{agonist} + EMG_{antagonist}] \times dt} \tag{4}$$

$$n = 1 - C_A \tag{5}$$

The co-contraction area C_A can also be represented as follows: C_A = common activities between the two group of muscles.

$$C_A = a.\exp b.x \tag{6}$$

where, a and b are constant parameters and x is the time.
where, EMG_{min} is the common area share by the EMG activity of bicep and tricep, $EMG_{agonist}$ and $EMG_{antagonist}$ are the full activities of the bicep and triceps muscle's. The activities of the both the muscles are normalized with respect to the maximum value of the activities of the same muscle.

2.2 Push-Pull Operation and Muscles activities

The push/pull motion of the arm is the flexion and extension of the arm about the elbow. The plane of the motion is vertical plane. The Push/pull activities with the muscle activation is shown in figure 2. In Ma's model there were no part of co-contraction and delay in the model which we have added in this new model.

3. DATA PROCESSING AND METHODOLOGY

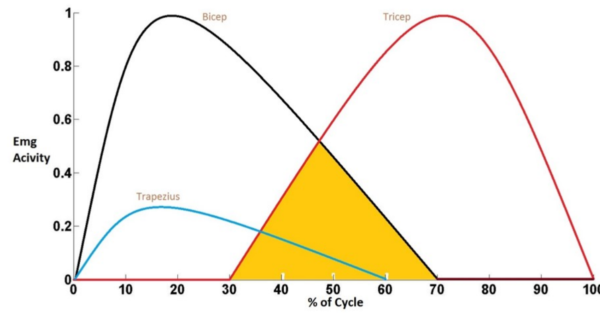

Figure 1: A representative plot of EMG activity of bicep, triceps and trapezius normalized with the maximum value of each muscle's activity for one cycle

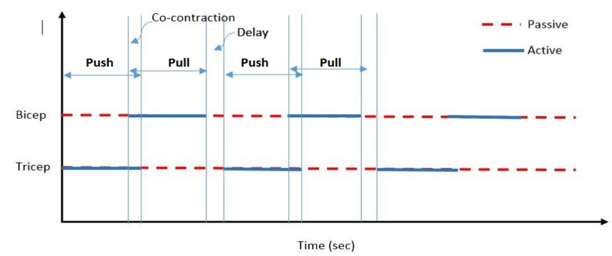

Figure 2: Push/Pull Motion and Muscles activities

3.1 Experiment Protocol

- The repetitive flexion and extension of the arm in a vertical plane as shown in figure 3
- The motion range is seventy degrees. The test repetition protocol continues till exhaution.
- Each cycle (flexion + extension) should be completed in 3 seconds.
- External load was 20% of MVC. MVC test every one minute.

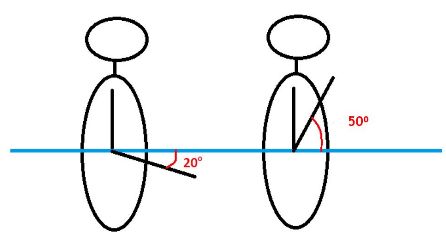

Figure 3: Arm movement range while flexion and extension in vertical plane

3.2 Data Acquisition

A Biodex system 3 research (Biodex medical,shirley, NY) isokinetic dynamo-meter was used to measure the value of elbow angle, velocity and torque. The Electromyographic sensor electrodes were put on Biceps, Tricep and Trapezius muscles to record their electrical activities. The frequency of data acquisition was set at 2000 Hz so that most of the activities get recorded.

3.3 Subject's description

The subjects (all male) details are given in the table 2. All the subjects were sportive.

S	Age	Wt.	Height	U. Arm	F.arm	Sport
1	28	89kg	185cm	29cm	26.5cm	Running
2	24	80.2kg	183.5cm	31.5cm	28cm	Gym
3	20	69.8kg	180.1cm	30cm	29.5cm	Handball
4	20	80.9kg	177cm	29.8cm	29cm	Handball
5	21	62.2kg	172.8cm	29.2cm	26.5cm	Tennis
6	25	61.1kg	164.8cm	26cm	24.5cm	Rugby
7	26	74kg	176cm	28.5cm	27cm	Tennis
8	27	66kg	181cm	29.5cm	26.5cm	wall climb
9	23	66.3kg	164cm	27cm	25.5cm	Swimming
10	26	85kg	184cm	29cm	26.5cm	Football

Table 2: Subjects anthropometric data and description

3.4 Data Processing and analysis

All the raw data were processed using standardized MATLAB program. Data processing includes noise filtering from raw EMG data with the filter frequency $10Hz$ for low pass filter and $400Hz$ for high pass filter and normalization of the data. The total number of cycles compared for all the ten subjects are 1998 cycles. All the cycles are normalized on time scale and compared. The cycle selection for flexion and extension phases is done according to the velocity change in each cycle. The collective EMG plots for Biceps, Triceps and Trapezius muscle are show in figure 4 and figure 5 for all the ten subjects and the collective comparison for the mechanical data position, velocity and torque is shown in figure 6 and figure 7 for all the ten subjects.
For figure4, 5, 6and 7 representations are as follows:
___ Blue color curve show mean EMG activity.
I Red bar plot on blue curve shows the standard deviation of all the EMG activities along the mean.
– Black dotted curves shows the maximum and minimum reach from the EMG activies. All the cycles are normalized according to the equation:

$$value_{Normalization} = value_{std}{}^{max} + 2\sigma \tag{7}$$

$value_{Normalization}$: Under it all the muscle activity will be normalized.
$value_{std}{}^{max}$: Maximum value of standard deviation along the mean.
2σ : σ values addition upto 2σ

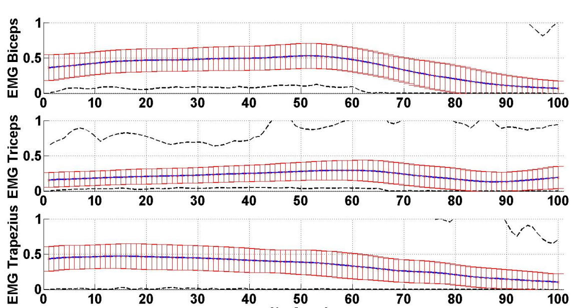

Figure 4: Mean and Standard deviation plots for EMG data of Bicep, triceps and trapezius in flexion phase for all subjects

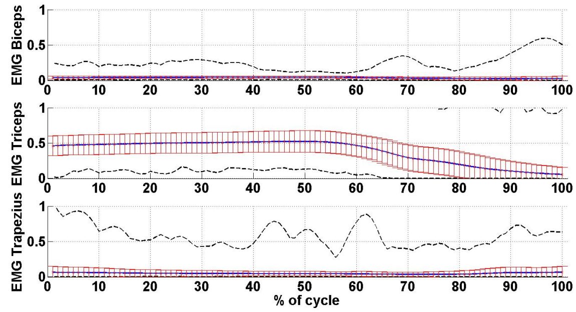

Figure 5: Mean and Standard deviation plots for EMG data of Bicep, Triceps and Trapezius in Extension Phase for all subjects

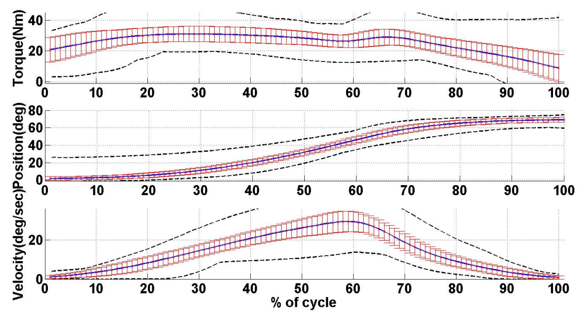

Figure 6: Mean and Standard deviation plots for velocity, position and torque in Flexion Phase for all subjects

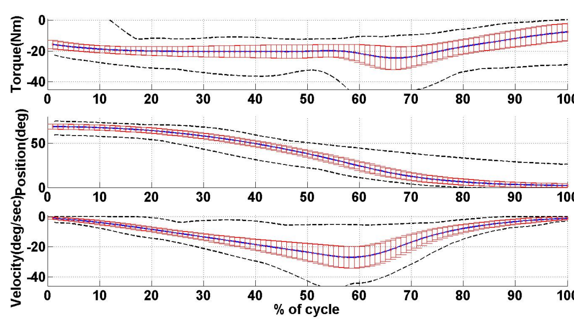

Figure 7: Mean and Standard deviation plots for velocity, position and torque in Extension Phase for all subjects

4. RESULTS AND DISCUSSION

The raw data obtained after the fatigue test is processed and the results and observations are discussed in this section. After processing the EMG data of all the muscle groups from figure 4, 5, 6 and 7, we can observe that when the biceps are active during flexion phase there are always some activities from the triceps and on the other hand when triceps are active during pull phase the biceps are almost passive or activities are very near to zero. We can also observe the co-activation of trapezius muscle with the activation of biceps. The activation of triceps with the biceps is co-contraction between two muscles during flexion phase.

The co-contraction area calculated by using equation 4 is fitted with the exponential equation 6 in section 2.1. The figure 8 - 17 shows the fitted graphs for the co-contraction percentage for test cycles of all ten subjects. In figures 8 - 17 blue dots show the percentage area of contraction during each extension-flexion cycle and red curve shows the exponential fit for the percentage co-contraction. This shows that the co-contraction percentage for activity between the muscles reduces as the fatigue test proceed or the muscles gets fatigued. By the equation 3 and 4 we can find n_i as shown in table 3, where i is the subject number:

n_i	n_1	n_2	n_3	n_4	n_5	n_6	n_7	n_8	n_9	n_{10}
n	0.6	0.5	0.67	0.6	0.59	0.65	0.64	0.7	0.5	0.7

Table 3: Co-contraction factor for each subject

We can notice that only the subject number 8 in figure 15 has increasing slope for the co-contraction area. This behavior can be associated with his sport activity which is wall climbing and very different from other subjects as shown in table 2.

The co-activation of the trapezius muscle is observed mostly in the flexion phase. The MVC values are measured between each protocol of one minute. We can see in most of the cases MVC decreases as fatigue increases. The MVC is same as Γ_{cem} used in our model. The theoretical and experimental evolution of Γ_{cem} is on the basis of k (fatigue rate) using equation 2 and equation 2 and calculated n_i and $C = 0.2$. The evaluation of fatigue parameter 'k' for Γ_{cem} extension is shown in figure 18, 20, 22, 24, 26, 28, 30, 32, 34 and 36. Similarly fatigue parameter 'k' evaluation for Γ_{cem} flexion is shown in figure 19, 21, 23, 25, 27, 29, 31, 33, 35 and 37. In these figures blue line shows the MVC measured for flexion and extension after each test protocol of 1 minute. The theoretical and experimental evolution of Γ_{cem} shows that the experimental values are well fit with in the theoretical model. The co-contraction factor have significant effect on the model. The fatigue rate increases with the input of co-contraction factor. The minimum, maximum and average value of 'k' for each subject are shown in table 4.

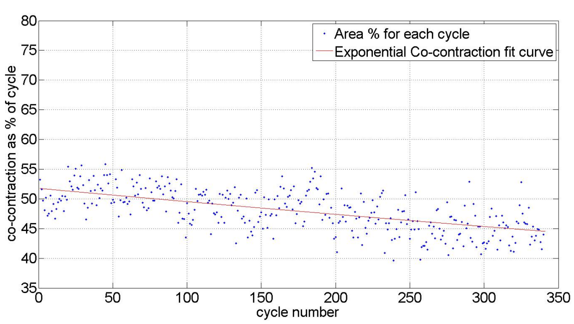

Figure 8: Exponential curve fit of co-contraction area for subject 1

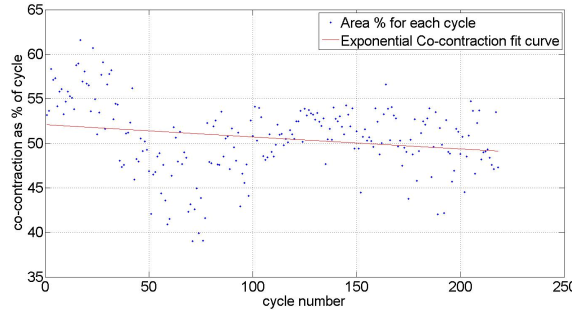

Figure 9: Exponential curve fit of co-contraction area for subject 2

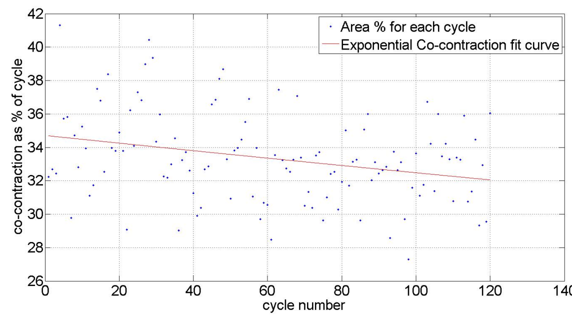

Figure 10: Exponential curve fit of co-contraction area for subject 3

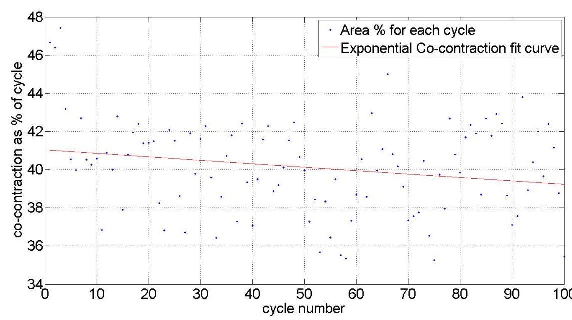

Figure 11: Exponential curve fit of co-contraction area for subject 4

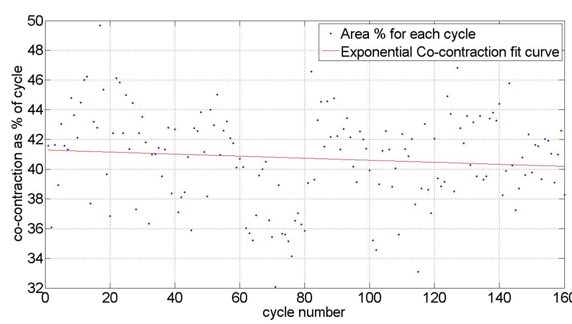

Figure 12: Exponential curve fit of co-contraction area for subject 5

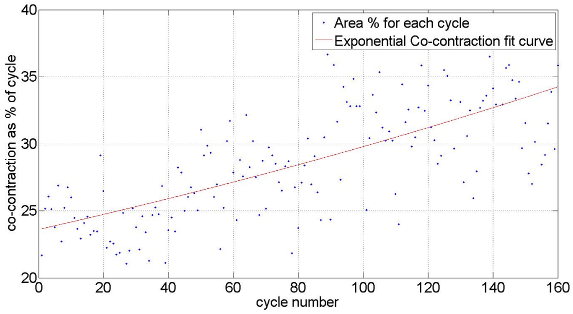

Figure 15: Exponential curve fit of co-contraction area for subject 8

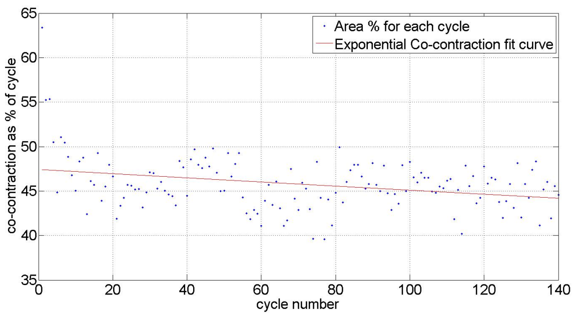

Figure 16: Exponential curve fit of co-contraction area for subject 9

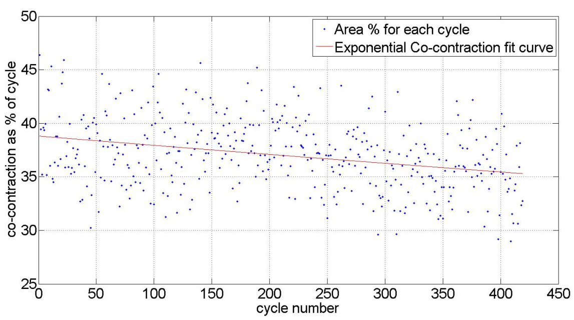

Figure 13: Exponential curve fit of co-contraction area for subject 6

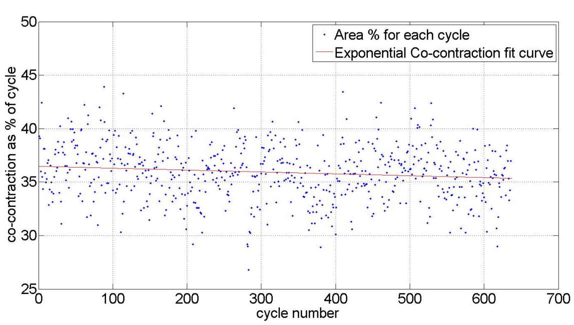

Figure 14: Exponential curve fit of co-contraction area for subject 7

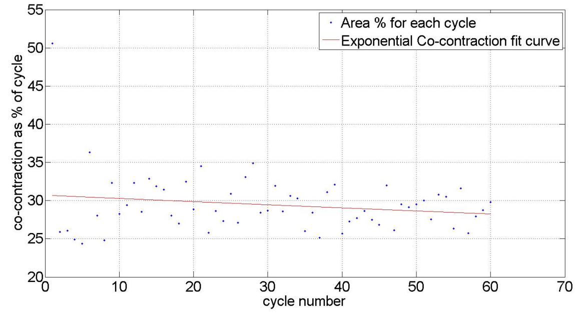

Figure 17: Exponential curve fit of co-contraction area for subject 10

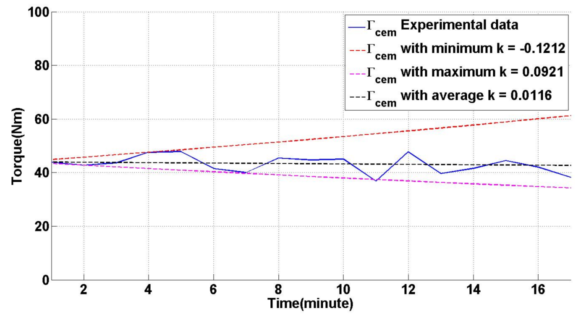

Figure 18: The extension in the subject 1

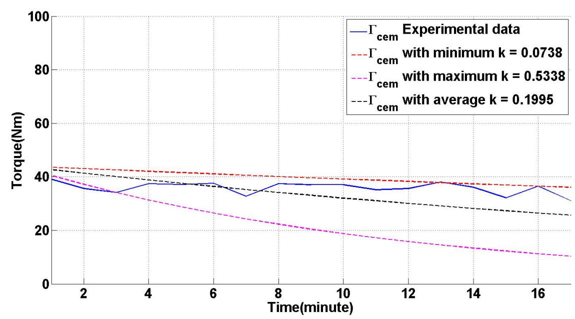

Figure 19: The flexion in the subject 1

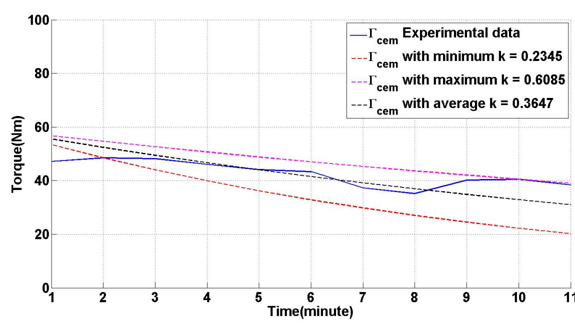

Figure 20: The extension in the subject 2

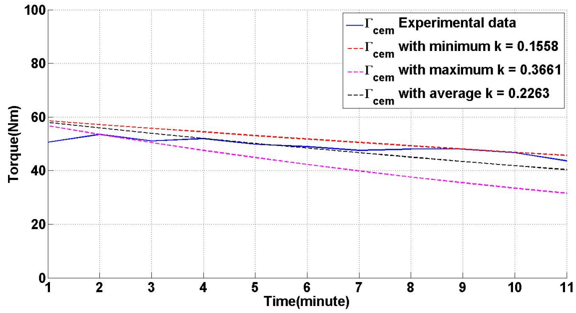

Figure 21: The flexion in the subject 2

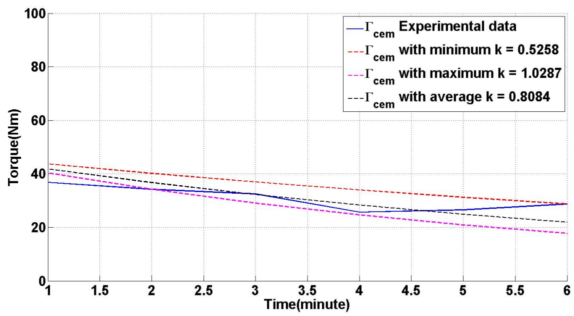

Figure 22: The extension in the subject 3

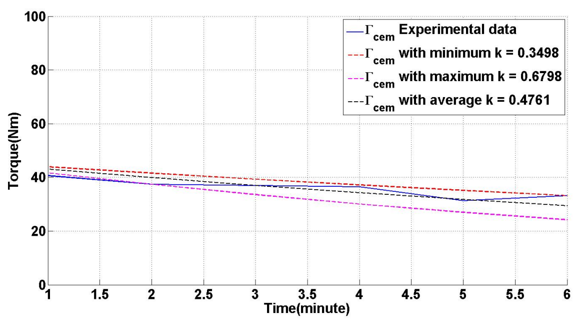

Figure 23: The flexion in the subject 3

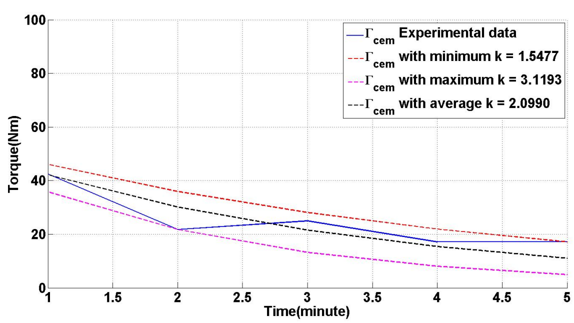

Figure 24: The extension in the subject 4

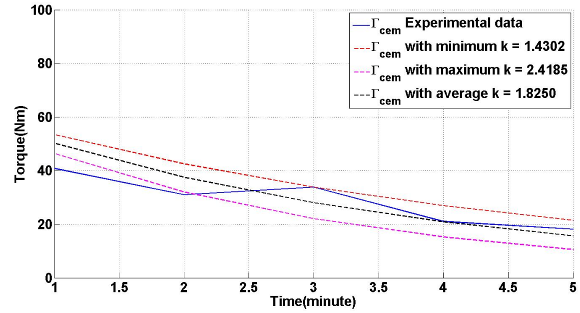

Figure 25: The flexion in the subject 4

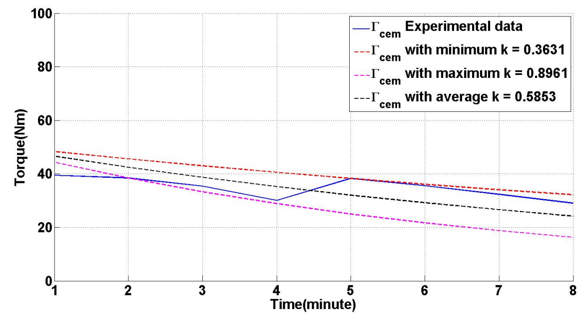

Figure 26: The extension in the subject 5

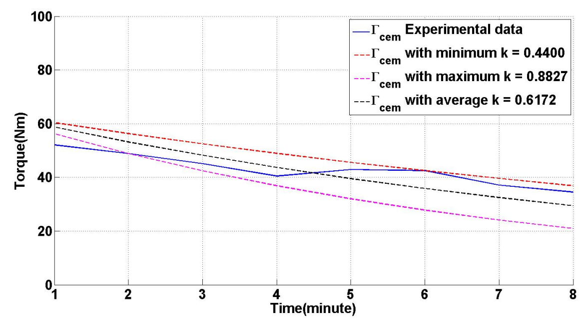

Figure 27: The flexion in the subject 5

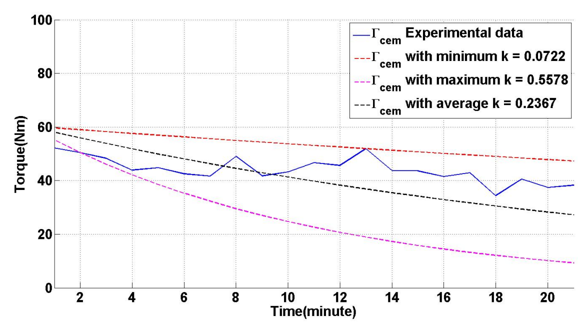

Figure 28: The extension in the subject 6

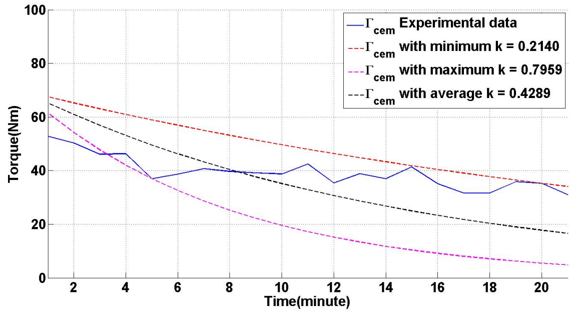

Figure 29: The flexion in the subject 6

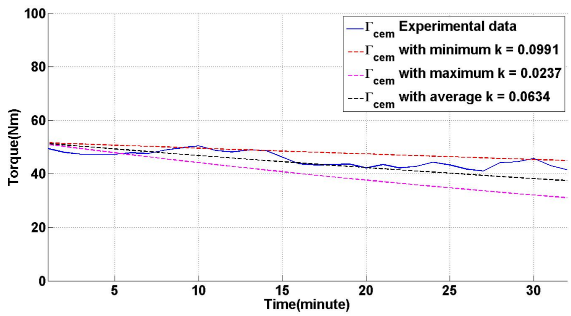

Figure 30: The extension in the subject 7

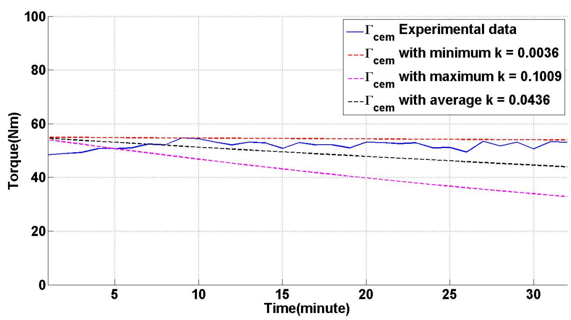

Figure 31: The flexion in the subject 7

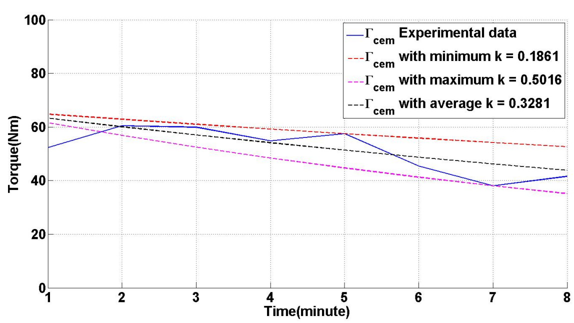

Figure 32: The extension in the subject 8

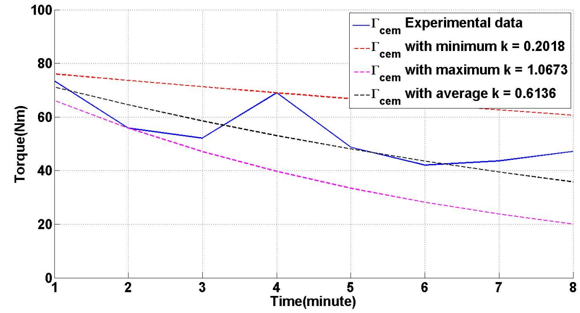

Figure 33: The flexion in the subject 8

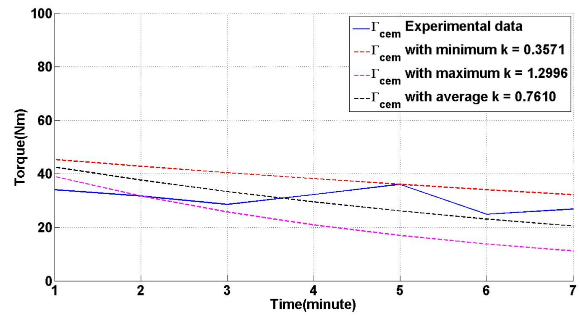

Figure 34: The extension in the subject 9

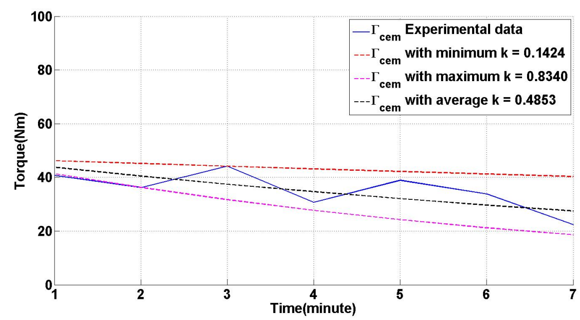

Figure 35: The flexion in the subject 9

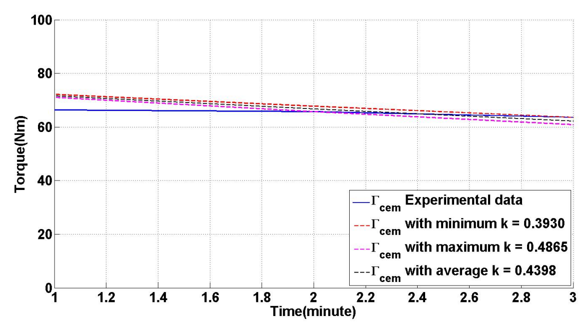

Figure 36: The extension in the subject 10

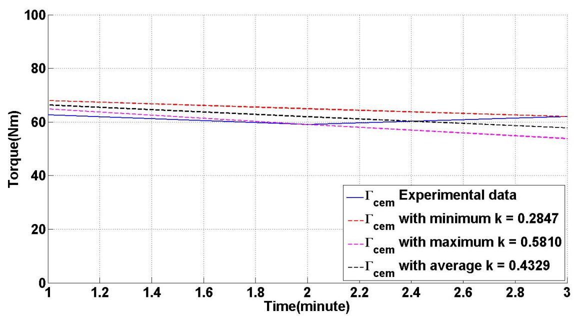

Figure 37: The flexion in the subject 10

	$k_{extension}$			$k_{flexion}$		
S	Min	Max	Avg	Min	Max	Avg
1	-0.1212	0.0921	0.0116	0.0738	0.5338	0.1995
2	0.2345	0.6085	0.3647	0.1558	0.3661	0.2263
3	0.5258	1.0287	0.8084	0.3498	0.6798	0.4761
4	1.5477	3.1993	2.0990	1.4302	2.4185	1.8250
5	0.3631	0.8961	0.5853	0.4400	0.8827	0.6172
6	0.0722	0.5578	0.2367	0.2140	0.7959	0.4289
7	0.0237	0.0991	0.0634	0.0036	0.1009	0.0436
8	0.1861	0.5061	0.3281	0.2018	1.0673	0.6136
9	0.3571	1.2996	0.7610	0.1424	0.8340	0.4853
10	0.3930	0.4865	0.4398	0.2847	0.5810	0.4329

Table 4: Experimentally calculated values of 'k'for flexion and extension motion

5. CONCLUSIONS

The proposed model for dynamic muscle fatigue includes the co-contraction parameter, unlike in any other existing model according to the author's knowledge. The results and analysis of the experimental data validates the most of the assumptions made for the proposed model. EMG analysis along with MVC helps to understand the muscle activities, also it justifies the significance of the co-contraction parameter in proposed dynamic muscle fatigue model. The experimental data also helps in validating the new dynamic muscle fatigue model.

6. ACKNOWLEDGMENTS

We are thankful to STAPS, University of Nantes, France for assistance in preparing and conducting the experiments.

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